Basic Soil Interpretations for Forest Development Planning: Surface Soil Erosion and Soil Compaction

Land Management Report NUMBER 63

ISSN 0702-9861

October 1991

BC

92-02520/

Basic Soil Interpretations for Forest Development Planning:
Surface Soil Erosion and Soil Compaction

by
W. W. Carr[1], W. R. Mitchell[2] and W. J. Watt[3]

[1] Consultant
Terrasol
P.O. Box 2092
Vancouver, B.C.
V6V 3T2

[2] Regional Pedologist
B.C. Forest Service
Kamloops, B.C.

[3] Regional Pedologist
B.C. Forest Service
Williams Lake, B.C.

October 1991

Ministry of Forests

Canadian Cataloguing in Publication Data

Carr, William W., 1952-
Basic soil interpretations for forest development planning

(Land management report, ISSN 0702-9861 ; no. 63)

Includes bibliographical references: p.
ISBN 0-7718-9055-9

1. Soil erosion - British Columbia. 2. Soil stabilization - British Columbia. 3. Forest management - British Columbia. I. Mitchell, W. R., 1929- II. Watt, W. J. (William J.), 1948- . III. British Columbia. Ministry of Forests. IV. Title. V. Series.

SD390.3C3C37 1991 634.9'2 C91-092208-X

© 1991 Province of British Columbia
Published by the
Forest Science Research Branch
Ministry of Forests
31 Bastion Square
Victoria, B.C. V8W 3E7

Copies of this and other Ministry of Forests titles are available from Crown Publications Inc., 546 Yates Street, Victoria, B.C. V8W 1K8.

ACKNOWLEDGEMENTS

The principal sources of funding for the development of this report were the Interpretation Working Group (Forest Science Research Branch, Victoria) and the Kamloops Forest Region (Research Section). The authors wish to thank the following people for their constructive reviews of both the earlier drafts and this final report: Gerry Still, Steve Chatwin, and Andy MacKinnon of the Forest Science Research Branch (Victoria); Terry Lewis (consultant); and Jim Schwab (Prince Rupert Forest Region).

PREFACE

"The pre-harvest silviculture prescription (PHSP) is a planning system at the operational level involving the collection of site-specific field data and the development of forest management prescriptions for cut blocks in advance of logging. The intent of the pre-harvest silviculture prescription is to bring about at the end of the logging process: (1) those conditions on the harvested area that will have best preserved the inherent site productivity and which will give rise to the establishment of a new stand best suited to the site for both volume and value production, and (2) those conditions which have also protected, or preserved the opportunity to manage for, other natural resources.

"The purposes of the PHSP program are to raise the overall level of forest management, to build upon documented results of differing forest management practices that are referenced to an ecological framework so that improved prescriptions can be developed leading to an improved long-term wood supply. An additional purpose is to reduce the overall costs of forest land management by assessing all natural resources present before harvest while all options are open and through cooperative planning and management avoid conflicts and their associated costs. Reduced logging and post-harvest rehabilitation costs can also be expected as a result of more efficiently planned layouts with significantly reduced site damage.

"It is the policy of the Forest Service that PHSPs will be carried out prior to harvest for all logging operations on land over which it has jurisdiction. The Forest Service will carry out PHSPs for areas within the small business program while for all other tenures, licensees will be responsible."

From: *Silviculture Policy 4.2: Pre-Harvest Silviculture Planning*, B.C. Ministry of Forests

TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii

PREFACE iii

1 INTRODUCTION 1

2 SOIL EROSION HAZARD 1
- 2.1 Surface Erosion Hazard Indices for Forest Land 2
- 2.2 A Key for Assessing Surface Soil Erosion Hazard 3
- 2.3 The Modified Surface Erosion Hazard Key 7

3 SOIL COMPACTION HAZARD 8
- 3.1 Effect of Soil Compaction on Soil Properties 8
- 3.2 Effect of Soil Compaction on Tree Growth 9
- 3.3 Soil Compaction Hazard Prediction 9
- 3.4 A Key for Assessing Forest Soil Compaction Hazard 9
- 3.5 The New Soil Compaction Hazard Key 12

4 SUMMARY 12

APPENDIX 1. Universal soil loss equation (USLE) 13

LITERATURE CITED 14

FIGURES

1. Erosion hazard key: Kamloops Forest Region 4
2. New surface erosion hazard key 5
3. Rainfall factors for the biogeoclimatic subzones and variants of interior British Columbia 6
4. Compaction hazard key: Nelson Forest Region 10
5. New compaction hazard key 11

1 INTRODUCTION

Forest land management interpretations, guidelines, and prescriptions are currently divided into three levels (Boyer 1970; Mitchell 1984). Basic interpretations are those developed using vegetation, environmental, and soil properties to ascertain the inherent nature of the treatment unit, particularly about the risk or "hazard" associated with potentially degrading processes. Secondary interpretations incorporate site or ecosystem properties and a number of basic interpretations to describe the sensitivity of sites to specific types of operations. Finally, management interpretations are developed using the above levels of interpretations, along with overall regional resource management objectives and economic constraints.

The basic and secondary interpretations incorporate information from biogeoclimatic and site classification and mapping, terrain and soil mapping, and environmental monitoring. Through their use in the planning phases of forest resource development, particularly in conjunction with the Pre-Harvest Silvicultural Prescription (PHSP), proper management interpretations can help raise the overall level of forest land management.

The recently proposed Interim Timber Harvesting Guidelines (May 1989) for the interior forest regions adopt the preceding approach. With information collected during the pre-harvest survey, basic interpretations of the sensitivity of the site to potentially degrading processes are made. The processes that are incorporated in this procedure are soil compaction, soil displacement, surface soil erosion, and mass wasting. The hazard keys for the interpretation are presented in the fieldguide insert *Developing Timber Harvesting Prescriptions to Minimize Site Degradation: Interior Sites* (Lewis *et al.* 1990). Once the individual hazards are assessed, an overall site sensitivity to soil degradation is derived. It is this overall degradation sensitivity that determines, within the current guidelines, the maximum allowable percentage of potentially degrading ground disturbance that can result from timber harvesting operations.

The purpose of this report is to provide background information on the development of the surface soil erosion and soil compaction hazard keys used in Lewis *et al.* (1989). These keys have evolved from models previously used in British Columbia. The models have been modified to reflect recent research and improved data presentation. Background information on the development of the other hazard keys, soil displacement and mass wasting, is available in Land Management Report No. 62 (Lewis *et al.* 1991).

2 SOIL EROSION HAZARD

In the natural forest environment, vegetation and forest litter protect the soil surface, resulting in a state of semi-equilibrium between erosional processes and soil-forming processes (Swanston 1974). The forester's main concerns with surface erosion are therefore over the implications of management activities such as road building or timber harvesting. These activities can remove the protective cover of litter and vegetation, exposing the soil to erosive forces of water, wind, and frost. If unchecked, surface erosion by water can progress through the following stages (Carr 1980):

Splash erosion:	the loosening or dispersion of soil particles by raindrop impact, resulting in the destruction of soil structure and the plugging of soil pores near the surface;
Sheet erosion:	the removal of a fairly uniform layer of soil from the land by surface runoff;
Rill erosion:	the formation of numerous small channels of several centimetres in depth;
Gully erosion:	the accumulation of water in narrow channels over a short period of time, resulting in the removal of soil to considerable depth.

The magnitude of accelerated surface erosion can be substantial and the consequences wide ranging. Soil erosion associated with forest road construction can annually remove about 200 m^3 of material per hectare of exposed slope (Dyrness 1970; Carr and Ballard 1980). When this material is stored in the road drainage system, the effectiveness of ditches and culverts is greatly impaired and major road stability problems can arise. Furthermore, a large proportion of road-initiated mass wasting events can be attributed to uncontrolled surface erosion and blockage of drainage structures.

Much of the eroded material may eventually enter surface waters, causing water quality problems. In Oregon, Fredricksen (1965) found a 250-fold increase in stream turbidity and sedimentation during the first rainstorms following construction of 2.5 km of forest road on a 100-ha watershed. Sediment levels continued to be higher than in a companion undisturbed watershed for the next 2 years. It was partly concern over water quality in coastal British Columbia which resulted in resource agencies and the forest industry adopting the Coastal Fisheries-Forestry Guidelines (1986).

A wide range of surface erosion and sediment control methods are suitable for use in the forest environment (Carr 1980 and 1985). By identifying with a hazard key the areas sensitive to surface erosion, and employing appropriate management strategies, foresters can greatly reduce surface erosion and sediment production. Prevention of erosion should be a high resource management priority. Where prevention is not feasible, however, the implementation of a well-prepared surface erosion and sediment control program, implemented concurrently with forestry activities, can cost-effectively mitigate the degrading impacts of surface erosion.

2.1 Surface Erosion Hazard Indices for Forest Land

A number of surface erosion prediction and hazard rating systems are used for forest land. These systems range from simple to complex, and include both empirical and diagnostic approaches. All the systems have advantages and disadvantages, and each can be useful as long as their capabilities and limitations are recognized. The most important consideration is that the chosen system should meet the objectives set by the user during operational planning procedures.

To assess the erosion hazard of a particular area properly, the forester must consider both the inherent erodibility of the soil and the magnitude of erosive forces. The inherent erodibility of a soil is influenced primarily by soil textural properties, such as cohesion, structure, and aggregate stability (Swanson 1974). The magnitude of the erosive forces is determined by the quantity of surface runoff and its associated energy. Runoff depends on precipitation frequency, intensity, and duration and on soil permeability. The kinetic energy of surface runoff is derived from topographic features such as slope length and steepness (Wischmeier 1959).

Most of the operationally employed empirical (or predictive) systems are process-oriented and follow the universal soil loss equation (USLE) originally developed for agricultural land (see details in Appendix 1) (Smith 1941; Musgrave 1947; Smith and Whitt 1947; Wischmeier and Smith 1958; Wischmeier 1959; Agricultural Research Service 1961; Wischmeier and Smith 1965; Foster and Wischmeier 1973). However, modifications are necessary to extend the use of the USLE to forest land.

Israelsen *et al.* (1980) modified the scope of the USLE to include slope length and steepness factors commonly found in road development. Dissmeyer and Foster (1985) and Van Dey Puy (1987) made other modifications based on ground or surface cover. Burns and Hewlett (1983) went further to include a sediment hazard factor which considers logging system layout. Unfortunately, the incorporation of new or modified factors increases both the complexity and data base requirements of the system. This greatly limits its practicality for use as a pre-harvest level planning tool.

Field testing of empirical soil erosion hazard indices on forest land has yielded variable results over a range of scales. De Vera (1981) found that a USLE-based system worked well on large watersheds after regional modification, but performed poorly for a single event or on a site-specific basis. Aldrich and Slaughter (1983) demonstrated a high degree of variability using the USLE to predict erosion from harvested forest sites. Rice and Datzman (1981) proved the California coastal erosion hazard index to be a poor predictor of erosion from logging.

To improve erosion prediction on forest and range land, the U.S. Department of Agriculture - Soil Conservation Service initiated the Water Erosion Prediction Project (Rosewell 1986). However, until a workable empirical system is available, an indirect or diagnostic approach to soil erosion hazard assessment appears to be more appropriate for the pre-harvest level of forest planning now used in British Columbia.

The indirect or diagnostic approach to hazard assessment is often referred to as an "expert" system. Important site factors are identified and the interpretation is then derived from a key or algorithm that has been developed by experts. Many expert keys tend to have a limited focus, with all factors either not included or oversimplified. They also reflect the bias of the developers and are usually overly conservative (McNutt and McGeer 1984). However, the user does gain a greater understanding of the problem by following the interpretive process. Also, such systems rely on a more limited, often qualitative, data base than the quantitative information required for the empirical models.

An example of a simple indirect system for soil erosion hazard determination is the key (Figure 1) used in the Kamloops Forest Region (Mitchell and Eremko 1987), modified from that used by the U.S. Forest Service, Region 6. This key parallels, for the most part, the approach utilized in the USLE by including the following basic factors:

Climate	- in terms of mean annual precipitation
Topography	- percent slope gradient
Soil depth	- to a restricting layer
Surface soil detachability	- inferred from aggregate structure or soil texture, and
Subsoil permeability	- rate of water penetration as inferred from soil texture and volume of coarse fragments.

These factors are given a numerical rating for each class, with the sum of all factor ratings giving a hazard classification.

The information needed to operate the key is more of a classification than a quantification of pertinent data, thus it requires little field time and no laboratory analysis. This latter point is an important factor in the selection of a field rating system. Although the Kamloops regional key has been effective in rating the surface erosion hazard for that forest region, we have identified several minor modifications that could improve its diagnostic capability. The changes incorporated into the new soil erosion hazard key (Figure 2) are primarily refinements in the definitions of the climate and topography factors, such that they more closely parallel those definitions used in the USLE. Field testing by Forest Service and forest industry personnel throughout the interior forest regions suggests that the new key is an effective, easy-to-use diagnostic tool for forest planning.

2.2 A Key for Assessing Surface Soil Erosion Hazard

The new key for basic interpretation of surface soil erosion hazard is a modification of the system formerly used in the Kamloops Forest Region (Mitchell and Eremko 1987). The changes are improved definitions of the climate and topography factors to enhance their contribution to the diagnostic process. The relative value or "weight" of these factors remained the same, except for depth to restricting layer which had its base point value changed.

The climate factor, which contributes from 3 to 12 points, is now defined by the rainfall factor (R) as used in the USLE, rather than by the mean annual precipitation. The R factors, recently calculated for British Columbia by Agriculture Canada, are based on historic rainfall frequency, intensity, and duration data, modified to account for snowmelt. These new R factors give a more realistic indication of the erosive energies of precipitation than do the gross rainfall data. Since the R factors correlate well with the biogeoclimatic classification of British Columbia forest land, each subzone/variant in the Interior has been assigned to an appropriate R factor range. The complete listing of R factor ranges for the interior forest regions is presented in Figure 3.

ENVIRONMENTAL FACTORS	Degree of contribution of factors			
	LOW	MODERATE	HIGH	EXTREME
CLIMATE Mean annual precipitation (mm)	**3** <400	**6** 400 - 699	**9** 700 - 1200	**12** >1200
TOPOGRAPHY Slope gradient (%)	**3** 0 - 15	**6** 16 - 30	**9** 31 - 60	**12** >60
DEPTH TO RESTRICTING LAYER (cm)	**2** >90	**4** 61 - 90	**6** 30 - 60	**8** <30
SURFACE SOIL DETATCHABILITY 1) Moist consistence	**1** very firm	**2** firm	**3** friable	**4** loose
or				
2) Texture	**1** SC, C, HC, SiC	**2** SiCL, CL, SCL	**3** SL, L, SiL	**4** LS, S, Si
SUBSOIL PERMEABILITY 1) Texture	**0.5** S, LS, SL	**1** L, SiL, Si	**1.5** CL, SCL, SiCL	**2** C, HC, SC, SiC
and				
2) Coarse fragments (% by volume)	**0.5** >75	**1.0** 50 - 75	**1.5** 25 - 49	**2** <25

SOIL EROSION HAZARD RATING	LOW	MODERATE	HIGH	EXTREME
Point total	<20	20 - 24	25 - 29	>29

FIGURE 1. Erosion hazard key: Kamloops Forest Region.

SITE FACTORS	Degree of contribution of factors			
	LOW	MODERATE	HIGH	VERY HIGH
CLIMATE	**3**	**6**	**9**	**12**
Rainfall factor (R)	<25	25-49	50-100	>100
TOPOGRAPHY				
	2	**4**	**6**	**8**
1) Slope gradient (%)	0-15	16-30	31-60	>60
and				
	1	**2**	**3**	**4**
2) Length / Uniformity	short broken	short unifo. .)	long broken	long uniform
DEPTH TO RESTRICTING LAYER	**1**	**2**	**3**	**4**
(cm)	>90	61-90	30-60	<30
SURFACE SOIL DETACHABILITY (0-15 cm)	**1**	**2**	**3**	**4**
Texture	SC, C, SiC	SiCL, CL, SCL	SL, L, SiL	LS, S, Si
SUBSOIL PERMEABILITY	**0.5**	**1**	**1.5**	**2**
1) Texture	S, LS, SL	L,SiL, Si	CL, SCL, SiCL	C, SC, SiC
and				
	0.5	**1**	**1.5**	**2**
2) Coarse fragments (% by volume)	>70	36-70	15-35	<15

SURFACE EROSION HAZARD RATING	LOW	MODERATE	HIGH	VERY HIGH
Point total	>16	16-22	23-29	>29

Surface Erosion Hazard Key Definitions:

Rainfall (R) factor - extract appropriate value from Figure 2 on page 6

Short slopes - <150 m between major (>10%) slope breaks

Long slopes - ≥150 m between major slope breaks

Broken slopes - variable, complex or benchy slopes

Restricting layer - bedrock; essentially impermeable, dense, compact or cemented layers; or permanent water table

FIGURE 2. New surface erosion hazard key (from Lewis *et al.* 1989).

Rainfall factors (R)			
<25	25 - 49	50 - 99	>100
all BG			
all PP			
IDFxh	IDFmw		
IDFxw	IDFww *	IDFww *	
IDFdm			
IDFdk			
MSxk	MSxc		
	MSdm		
	MSdk		
	MSdc		
	MSmm		
	MSmk		
	MSmw		
SBSdh	SBSmh	SBSvk	
SBSdw	SBSmw		
SBSdk	SBSmm		
SBSmc *	SBSmc *		
SBSmk1	SBSmk2		
	SBSwk		
SBPSxc	SBPSmk		
SBPSdc			
SBPSmc			
BWBSdk			
BWBSmw2	BWBSmw1		
BWBSwc3	BWBSwc1&2		
ESSFxc	ESSFdk	ESSFwc	ESSFvc
ESSFxv	ESSFdc	ESSFwm	ESSFvv
	ESSFdv	ESSFwv	
	ESSFmm		
	ESSFmk		
	ESSFmc		
	ESSFmv		
	ESSFwk *	ESSFwk *	
	all SWB		
	ICHxm	ICHvc	
	ICHxw	ICHvk	
	ICHdk		
	ICHdm		
	ICHdw		
	ICHmm		
	ICHmw		
	ICHmk		
	ICHmc		
	ICHwk *	ICHwk *	
		CWHds	CWHws1&2
		CWHms	
			MHm

* *These varients encompass two R factor ranges. Use local experience in deciding the appropriate R factor to apply in the keys.*

FIGURE 3. Rainfall factors for the biogeoclimatic subzones and variants of interior British Columbia.

The topography factor in the new key is now divided into two components, slope gradient (%) and length/uniformity. This presentation embodies the concept of the slope length/steepness (LS) factor of the USLE. The greater the slope gradient of a defined site unit or treatment unit, the higher the probability of very steep, denuded slopes resulting should some form of deep disturbance or construction take place.

The other components contributing to the erosive energy of surface runoff are slope length and uniformity. The length designation, long (≥150 m) or short (<150 m), considers the potential distance that surface flow may travel on exposed mineral soil within a given treatment unit. The longer the unit, the longer the potential run and the greater the erosive energy. The uniformity modifier, broken (i.e., benched or undulating) or uniform (i.e., smooth and straight), relates to the possibility of limiting the length of run of surface flow through the strategic use of topographic breaks during site development. The combination of length and uniformity classes indirectly addresses the elements of the LS factor used in the USLE in a broader, pre-development context.

Three soil factors or properties are also used in the new key: depth to a restricting layer, surface soil detachability, and subsoil permeability. Surface soil detachability, as implied by the average soil texture in the 0-15 cm layer, indicates the soil's resistance to particle detachment and transport. Soil structure is not specifically included because the structure of most of interior British Columbia's surface soils is relatively weak as a result of low organic matter content. Soils that exhibit a high degree of cohesion or aggregate stability, primarily provided by clay and organic matter content, are far more resistant to erosion than non-cohesive soils dominated by sand or silt particles.

Depth to a restricting layer that prevents deep percolation (i.e., bedrock, compact layer, etc.) and subsoil permeability (inferred from texture and coarse fragment content) combine to indicate the potential for surface runoff to occur, a requirement for surface erosion. Since these factors are complementary, they have each been assigned point values ranging from 1 to 4. This represents the only point value change between the Kamloops and current hazard keys in the weighting of factors. The original value of 2 to 8 for depth to restricting layer, which can include impermeable, fine-textured soil horizons, allowed for a potential double counting (and overemphasis) of subsoil properties.

The soil factors included in the hazard key correlate directly to the soil erodibility factor (K) of the USLE. This is justified since the new key pertains to soil materials exposed by forestry operations that generally have low organic matter content and poor structure. Thus, with these properties being unfavourable and less variable, subsoil texture and overall permeability become the primary factors in the USLE nomograph for determining soil erodability (Israelsen *et al.* 1980).

The final surface erosion hazard class is determined from the sum of the numerical values given to the site and soil factors. Each factor has been assigned a value such that the weighted relationship between the factors parallels that found in the USLE. The four-level rating system (low, moderate, high, and very high) that has proven useful in the Kamloops and U.S. Forest Service surface erosion hazard keys has been retained, following appropriate modification of the hazard class boundaries.

2.3 The Modified Surface Erosion Hazard Key

The surface erosion hazard key now represents an indirect or diagnostic approach to hazard evaluation, and parallels the predictive approach taken in USLE-based systems. In the new key, soil, topography, and climate factors are weighted equally, each contributing from 3 to 12 points. The occurrence of surface runoff is a function of climate, depth to a restricting layer, and subsoil permeability. In the USLE, the rainfall factor (R) and permeability components of erodibility (K) address this concept.

The potential erosive energy of surface runoff in this key is a function of slope gradient and slope length/uniformity. This parallels the slope length and steepness (LS) factor in the USLE, although the new key addresses this concept in an indirect manner that can be applied at the pre-development stage. Soil erodibility, or surface soil detachability in the new key, is inferred by soil texture, the dominant factor in the USLE determination of inherent erodibility (K). The modified hazard key now agrees more closely with the relative weights and definitions of the factors that determine soil erosion as predicted in the USLE; and it has proven to be an effective planning tool in trials throughout the interior forest regions.

3 SOIL COMPACTION HAZARD

Most timber harvesting in the Interior forest regions of British Columbia is with ground-based equipment. These types of systems, which also have limited use in coastal regions, necessitate the construction of landings, skidroads, and skidtrails which are subject to the compacting forces of harvesting equipment. Soil compaction can drastically alter soil characteristics and adversely affect site productivity. Landings can occupy 3-5% of the average cutblock, with the percentage in skidroads and skidtrails ranging from 14 to over 30% (Hatchell *et al.* 1970; Froehlich 1973; Smith and Wass 1979; Schwab and Watt 1981; Carr and Mitchell 1987). Soil compaction alters the physical arrangement of soil particles, resulting in an increase in soil density. The increased soil density is largely at the expense of soil macropores, and adversely affects soil air, water, and thermal regimes (Ruark *et al.* 1982). The degree and areal extent of changes in soil properties depends on the harvesting system used, site conditions during the operation, and soil texture (van der Weert 1974). The resulting effect on site productivity is a complex interaction between soil texture, the impact on chemical, biological, and physical properties, and tree species (Greacan and Sands 1980).

3.1 Effect of Soil Compaction on Soil Properties

Change in soil bulk density is the measure of soil compaction most commonly used to infer how compaction is affecting the factors that determine tree growth, including soil strength (resistance to root penetration), air permeability, infiltration capacity, and hydraulic conductivity. However, the relative importance of these factors to tree growth is confounded by soil texture. Coarse-textured soils, with their higher initial total porosity, are less sensitive than fine-textured soils to a given change in soil density. In contrast, fine-textured soils, with their generally lower total porosity and aeration porosity, are highly sensitive to even slight changes in density and can rapidly approach growth-limiting thresholds. Consequently, caution must be used when impacts for different sites are being compared.

Increases in soil density due to landing, skidroad, and skidtrail construction and use are greatest at the soil surface and decline rapidly with depth. The increases in the density of the surface soil layer (0-10 cm) range from 15 to 60% for skidroads (Steinbrenner and Gessel 1955a&b; Dickerson 1976; Smith and Wass 1985; Carr and Mitchell 1987) and from 25 to 88% for landings (Perry 1964; Carr 1987; Arnott *et al.* 1988). Although the increase in density tapers off quickly with depth, it is often still evident at 30 cm (Haines *et al.* 1975; Froehlich 1979; Wert and Thomas 1981; Gent *et al.* 1983; Carr 1987; Arnott *et al.* 1988). Changes in related soil physical characteristics have also been documented, including total and aeration porosity, air permeability, water infiltration, and hydraulic conductivity (Steinbrenner and Gessel 1955b; Dickerson 1976; Gent *et al.* 1983; Hildebrandt 1983; Hager and Sieghardt 1984; Carr and Mitchell 1987). The longevity of changes associated with soil compaction may be less than 10 years at the soil surface (Thorud and Frissell 1976), but often persist for over 30 years at depth (Perry 1964; Wert and Thomas 1981; Jakobsen 1983).

Compaction also affects the biological and chemical aspects of forest soils. Reduced soil aeration due to compaction decreases root respiration and microbial activity (Cannell 1977). Poor aeration, in conjunction with higher soil strength, has also resulted in decreased mychorrizal growth and penetration of mycelia (Skinner and Bowen 1974; Mitchell *et al.* 1982). It can further abet a decline in productivity by creating chemical reducing conditions in the soil, which may result in some nutrients becoming unavailable, or even toxic, to plant uptake (Castillo *et al.* 1982; Mitchell *et al.* 1982).

The destruction of soil structure and the alteration of the macropore/micropore balance may result from the application of compacting forces without a corresponding increase in soil density. Commonly known as "puddling," this condition occurs when the soil is saturated and buoyant forces oppose the compression of the soil particles. However, soil structure is dramatically altered, often resulting in platey structure and loss of air or water exchange capability. Puddling affects soil productivity much like soil compaction does.

3.2 Effect of Soil Compaction on Tree Growth

The impact of soil compaction on tree growth depends on the degree of compaction, the soil texture, and the tree species (Cannell 1977; Halverson and Zisa 1982). Although the effects of higher soil strength (reflected by an increase in bulk density) and reduced aeration are difficult to separate, several studies define critical bulk density levels that begin to affect root growth and development. Bulk densities above 1400 kg/m^3 (1.4g/cc) have been shown to restrict loblolly pine root growth, branching, and penetration (Mitchell *et al.* 1982; Gent *et al.* 1983). Hildebrandt (1983) found that a density of 1250 kg/m^3 in loamy soils hindered root penetration and development of beech seedlings, with a density of 1350 kg/m^3 halting root growth. Minko (1975) showed 1500 kg/m^3 to be a critical density for radiata pine growth in a silty-clay nursery soil, with improved seedling height and root growth occurring as the soil density approached 1200 kg/m^3. Heilman (1981) demonstrated a decline in Douglas-fir seedling root penetration in loam and sandy loam soils as the bulk density increased from 1330 to 1770 kg/m^3. Overall, a soil density (corrected for coarse fragment content) of 1300-1400 kg/m^3 appears to be a critical threshold level where tree root growth begins to be affected for a range of soil types and tree species.

Aside from its effect on root development, soil compaction can also cause regeneration delays (Steinbrenner and Gessel 1955b; Smith and Wass 1979) and reduced stocking (Steinbrenner and Gessel 1955b; Hatchell *et al.* 1970; Wert and Thomas 1981). Reported estimates of volume reduction on skidroads range from 45% after 26 years (Perry 1964) to greater than 70% after 32 years (Wert and Thomas 1981; Jakobsen 1983). Compaction is a major contributor to harvesting-induced volume reductions which have been projected over the entire cutblock to be in the 10-15% range (Smith and Wass 1979; Wert and Thomas 1981; Carr 1987).

3.3 Soil Compaction Hazard Prediction

Any attempt to predict soil compaction caused by timber harvesting operations is confounded by several factors. Froehlich *et al.* (1980) found standard Procter curves to be poor predictors of compaction caused by forestry equipment. The forces from forest harvesting equipment tend to be more dynamic and of lesser magnitude than the forces used in the Procter test. Additionally, the coarse fragment content of many forest soils can reduce the reliability of standard soil strength tests.

Site factors at the time of operation can further confound the prediction of soil compaction. The magnitude and impact of compacting forces can be increased or decreased by operating conditions. It is possible, for example, for a low hazard site to be severely affected by operating equipment under unfavourable conditions. The compaction hazard index used in the Nelson Region (Figure 4) addresses this problem by incorporating a season of logging factor.

3.4 A Key for Assessing Forest Soil Compaction Hazard

In lieu of a reliable predictive model for forest soil compaction, and in recognition of the major role of site conditions, a new compaction hazard key is presented in Figure 5 (from Lewis *et al.* 1989). This key begins with a simplification of the guide used in the Nelson Forest Region (Comeau *et al.* 1982) to determine the basic compaction hazard. It also includes a list of impact modifiers to assist in the planning of harvesting operations. These impact modifiers provide a generalization of the role of various site factors and conditions that may influence the eventual impact of equipment operation on soil productivity. They do not affect the compaction hazard, but are included only to encourage the planning of operations that minimize impacts.

The hazard rating for sensitivity to soil compaction was developed from the maximum dry density according to the standard Procter method, and adjusted by drainage and permeability characteristics (Sowers and Sowers 1970). The maximum dry density level rates the soil's relative degree of compactibility, which relates to threshold bulk density values for soil strength or resistance to root penetration. Modifying the texture density rating by water drainage and air permeability characteristics recognizes the importance of air and water exchange in determining the growth-limiting bulk density for different soil textures (Daddow and Warrington 1983). Coarse-textured soils, although high on the density rating, still offer reasonable aeration porosity. On the other hand, fine-textured soils with low compactibility sacrifice a major portion of their macropores during even minimal compaction, which dramatically affects soil aeration and hydrological properties.

SOIL CHARACTERISTICS		SEASON	BIOGEOCLIMATIC SUBZONE AND MOISTURE REGIME											
			PPBG a, d, f IDF a, b, c, d, e, j MS c				ICH e, m SBS m, MS b ESSF d				ICH w, v ESSF e, f, m, w, u			
			0-4	5-6	6-7	7-8	0-4	5-6	6-7	7-8	0-4	5-6	6-7	7-8
c.f. > 70%	**Fragmental**	Spring												
		Summer												
		Fall												
		Winter						L						
c.f. 35 - 70%	**Sandy Skeletal** S, LS	Spring												
		Summer												
		Fall												
		Winter												
	Loamy Skeletal L, CL, SL, SiCL, SCL, SiL, Si	Spring	H	H	M	M	H	H	M	M	H	M	M	M
		Summer	L	M	H	M	L	M	H	M	H	H	H	M
		Fall	L	L	H	M	M	M	H	M	M	H	H	M
		Winter	L	L	L	M	L	L	L	M	L	L	L	M
	Clayey Skeletal C, HC, SiC, SC	Spring	M	M	L	L	M	M	L	L	M	L	L	L
		Summer	L	L	M	L	L	L	M	L	M	M	M	L
		Fall	L	L	M	L	L	L	M	L	L	M	M	L
		Winter												
Coarse fragment (c.f.) < 35%	**Sandy** S, LS	Spring												
		Summer						L						
		Fall												
		Winter												
	Loamy L, CL, SL, SCL	Spring	H	H	M	M	H	H	M	M	H	M	M	M
		Summer	L	M	H	M	L	M	H	M	H	H	H	M
		Fall	L	L	H	M	M	M	H	M	M	H	H	M
		Winter	L	L	L	M	L	L	L	M	L	L	L	M
	Silty Si, SiL, SiCL (and fine sands)	Spring	H	H	M	M	H	H	M	M	H	M	M	M
		Summer	L	M	H	M	L	M	H	M	H	H	H	M
		Fall	L	L	H	M	M	M	H	M	M	H	H	M
		Winter	L	L	L	M	L	L	L	M	L	L	L	M
	Clayey C, HC, SiC, SC	Spring	M	M	L	L	M	M	L	L	M	M	L	L
		Summer	L	L	M	L	L	L	M	L	M	H	M	L
		Fall	L	L	M	L	L	L	M	L	L	H	M	L
		Winter	L	L	L	L	L	L	L	L	L	L	L	L

Spring - (March 16 - June 15); Summer - (June 16 - September 15); Fall - (September 16 - December 15); Winter - (December 16 - March 15).

Note: Soils with moderate or high ratings should be avoided when moist or following precipitation at any time.

FIGURE 4. Compaction hazard key: Nelson Forest Region (from Comeau *et al.* 1982).

SOIL TEXTURE (0 - 30 cm)		HAZARD RATING[1] (moist)
c.f. > 70%	**Fragmental**	**L**
Skeletal: c.f. 35 - 70%	**Sandy** S, LS[2]	**L**
	Loamy & Silty SL, L, Si, SiL	**M**
	Clayey SC, SiCL, SCL, CL SiC, C	**H**
Coarse fragment (c.f.) < 35%	**Sandy** S, LS	**L**
	Loamy SL, L	**M**
	Silty Si, SiL (and fine sands)	**H**
	Clayey SC, SiCL, SCL, CL SiC, C	**VH**

[1] L = Low; M = Moderate; H = High; VH = Very high

[2] Listed in order of increasing hazard.

IMPACT MODIFIERS: Seasonal Factors	
Climate Dominated	**Impact Adjustment**
Soil moisture	
Dry	- 1 class
Wet	+ 1 class
Snow pack	
0 - 1 m	no change
> 1 m	
granular	- 1 class
compressible	- 2 classes
Frozen ground	
0 - 15 cm	no change
16 - 50 cm	- 1 class
51 cm +	- 2 classes

IMPACT MODIFIERS: Surface Condition Factors	
LF Dominated[3]	**Impact Adjustment**
Forest floor	
≥ 20 cm	- 1 class
< 20 cm	no change
Scalping	
≤ 25 cm	+ 1 class
> 25 cm	+ 2 classes

[3] LF dominated (fibrous) forest floors have significant bearing strength and provide some protection for the mineral soil.

FIGURE 5. New compaction hazard key (from Lewis *et al.* 1990).

The site factors that modify the effects of compacting forces include soil moisture, snowpack, frozen soil, and surface condition. Changes in soil moisture, for example, affect the ease of compactibility (Moehring and Rawls 1970). Moisture is a lubricating agent for soil particles, and thus increased moisture content will facilitate compaction while drier conditions will resist compaction.

The season of logging comes into play with the snow pack and frozen soil modifiers, and represents one of the major planning opportunities available to minimize the impact of timber harvesting on the soil. The use of a compressible snow pack can greatly reduce compacting forces on the soil by acting as a cushion. The snow quality should be such that it will compact and form a running surface for equipment by being moist and non-granular. From discussions with operational personnel, at least 1 m of snow of acceptable quality is generally viewed as being adequate to offset equipment impacts. A two-level impact adjustment factor is used in the key based on snow quality.

The presence of frozen soil conditions can also increase the soil resistance to compacting forces. However, no impact reduction is recognized for a shallow frozen layer (<15 cm). Although the degree of compaction in the surface layer may be somewhat reduced, the energy can be transferred to the unfrozen soil, resulting in subsoil compaction (Mace *et al.* 1971). As the depth of frozen soil increases beyond 15 cm, the impact of soil compaction can be significantly reduced. In this way, the deeper the frozen soil, the less the effect of soil compaction.

The last impact modifier, surface condition, primarily takes into account the type of skidding path, either unbladed skidtrails or constructed skidroads, used during the harvesting operation. If skidtrails are used, a deep (>20 cm), fibrous forest floor (LF dominant) layer, as determined in the initial field evaluation, may cushion the soil from compacting forces for the first few passes of harvesting equipment (Tackle 1962; Jakobsen and Moore 1981). With bladed or excavated skidroads, compacting forces are applied directly to the mineral soil. Shallow scalping (<25 cm) removes the forest floor and surface horizons that have better soil structure, and thus lowers the resistance to compaction and increases impact. With deep scalping (>25 cm), the previous impact can be aggravated by the exposing of higher density subsoil material (Smith and Wass 1985; Carr 1987). A two-level impact modifier is used in the key to describe the role of soil scalping.

3.5 The New Soil Compaction Hazard Key

The soil compaction hazard key reflects the inherent compactibility of the soil. The impact modifiers help foresters determine the ultimate impact of forestry operations on soil density. By understanding the role and potential influence of various impact modifiers, the forester can better plan harvesting operations to meet the soil management goal of maintaining site productivity.

4 SUMMARY

The soil erosion and compaction hazard keys presented for basic interpretations in the forest development planning process are modifications of previously used systems. The modifications reflect advances in forest soil research and improved factor definition that will improve the keys' predictive capability. Neither key requires the collection of field data other than that traditionally gathered during a pre-harvest assessment, or during standard biogeoclimatic or forest site mapping.

The soil erosion hazard key was modified to more closely approximate the definition and weighting of factors embodied in the USLE. This is not necessarily the final modification; another review should be undertaken once the Water Erosion Prediction Project is completed. The soil compaction hazard key should also undergo regular scrutiny, particularly for regional applicability of the impact modifiers. Through continued forest soil research and operational verification, the diagnostic capability of both indices may be improved. In their current form, more than 500 workshop participants have shown that these hazard keys can readily be used by field personnel to assess the surface soil erosion and soil compaction components of site sensitivity. This type of pre-harvest assessment should, in turn, result in better planning of timber harvesting operations and minimized site degradation.

APPENDIX 1. Universal soil loss equation (USLE).

The modified USLE most commonly used is (Israelsen *et al.* 1980):

$$A = R^{*} K^{*} LS^{*} VM$$

in which:

A = computed **amount** of soil loss per unit area for the time interval represented by factor R

R = **rainfall** factor

K = soil erodibility factor

LS = topography factor (**length** and **steepness** of slope)

VM = erosion control factor (**vegetation management**)

When values for these factors are known for a specific area and site condition, the average amount of surface erosion can be predicted.

The rainfall factor "R" addresses both the rainfall intensity and total kinetic energy of regional precipitation. The R value is computed from rainfall records of individual storms, and requires a long-term record. The R values for British Columbia range from 10 to over 100. Since the R value is derived from probability statistics and is not a precise estimator, its primary value is as a predictive tool (Israelsen *et al.* 1980).

The soil erodibility "K" factor represents the inherent capability of the soil to resist erosive energies related to particle detachment and transport. The K factor is often determined using a nomograph (Wischmeier 1971), which incorporates the following factors:

Soil texture:	using % silt and very fine sand and % sand (0.10 - 2.0 mm)
Organic matter content:	percentage
Soil structure:	very fine granular to massive
Permeability:	rapid to very slow

Values for the K factor range from 0.1 to 0.7.

The topographic factor "LS" is a representation of the erosive energy of surface runoff. Although originally developed for relatively flat, agricultural land, values for steep (up to 100% gradient) and long (up to 1500 feet) slopes have been derived by Wischmeier and Smith (1973). These values range from 0 to 30.

The erosion control factor "VM", which is not pertinent to prediction at the PHSP level, indicates the effectiveness of an erosion control measure. The more effective the measure, the lower the value. A rating of 0.1 means that only 10% of the potential erosion will be realized. This factor will be of benefit in management interpretations.

LITERATURE CITED

Agricultural Research Service. 1961. A universal equation for predicting rainfall-erosion losses. U.S. Dept. Agric., ARS-22-66.

Aldrich, J.W. and C.W. Slaughter. 1983. Soil erosion on subarctic forest slopes. J. Soil Water Conserv. 38(2):115-118.

Arnott, J.T., W.W. Carr and A.C. Waines. 1988 . Establishing forest cover on winter landings in the Central Interior of British Columbia. For. Chron. (April):121-126.

Boyer, D. 1970. Soil management interpretations. Mimeo. U.S. For. Serv., Region 6, Portland, Ore.

B.C. Ministry of Environment. 1978. Proposed guidelines for the watershed management of Crown lands that are used for community water supply. Victoria, B.C.

B.C. Ministry of Environment and Ministry of Forests. 1987. Coast fishery-forestry guidelines. Queen's Printer, Victoria, B.C.

B.C. Ministry of Forests. 1987. Pre-harvest silvicultural prescription. Silviculture Policy 4.2. Victoria, B.C.

Burns, R.D. and J.S. Hewlett. 1983. A decision model to predict sediment yield from forest practices. Water Res. Bull. 19(1):9-13.

Cannell, R.Q. 1977. Soil aeration in relation to root growth and soil management. Appl. Bio. 1977 (2):1-86.

Carr, W.W. 1980. A handbook for forest roadside erosion control in British Columbia. B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 4.

_____ . 1985. Watershed rehabilitation options for disturbed slopes on the Queen Charlotte Islands. B.C. Min. For., Victoria, B.C. Land Manage. Rep. No. 36.

_____ . 1987. The effect of landing construction on some forest soil properties: a case study. B.C. Min. For. Lands, Res. Br., Victoria, B.C. FRDA Rep. 003.

Carr, W.W. and T.M. Ballard. 1980. Hydroseeding forest roadsides in British Columbia for erosion control. J. Soil Water Conser. 35(1): 33-35.

Carr, W.W. and W.R. Mitchell. 1987. Timber harvesting disturbance on steep slopes. Abstract in Proc. of Workshop on Long Term Forest Productivity, March 30 - April 1, 1987, Ore. State Univ., Corvallis, Ore.

Castillo, S.R., R.H. Dowdy, J.M. Bradford, and W.E. Larson. 1982. Effects of applied mechanical stress on plant growth and nutrient uptake. Agron. J. 74:256-7.

Comeau, P.G., M.A. Comeau, and G.F. Utzig. 1982. A guide to plant indicators of moisture for southeast British Columbia, with engineering interpretations. Min. For., Victoria, B.C. Land Manage. Handb. No. 5.

Daddow, R.L. and G.E. Warrington. 1983. The influence of soil texture on growth - limiting soil bulk densities. Proc. Soc. Amer. Foresters (1983):252-256.

De Vera, M.R. 1981. Assessment of sediment yield using the universal soil loss equation. *In* Erosion and Sediment Transport in Pacific Rim Steeplands. I.A.H.S. Publ. No. 12:400-414.

Dickerson, B.P. 1976. Soil compaction after tree-length skidding in northern Mississippi. Soil Sci. Soc. Am. J. 40:965-966.

Dissmeyer, C.E. and C.R. Foster. 1985. Modifying the universal soil loss equation for forest land. *In* Soil Erosion and Conservation. S.A. El-Swafi, W.C. Moldenhauer, and A. Lo. (editors). Soil Water Conserv. Soc., Ankeny, Iowa, pp. 480-485.

Dyrness, C.T. 1970. Stabilization of newly constructed road backslopes by mulch and grass-legume treatments. U.S. Dep. Agric. For. Serv., Pac. NW For. Range Exp. Sta., Portland Ore. Res. Note PNW-123.

Foster, G.R. and W.H. Wischmeier. 1973. Evaluating irregular slopes for soil loss prediction. 1973 Annual Meet. ASAE, Univ. Kentucky, Lexington, Ky. Paper No. 73-227.

Fredricksen, R.L. 1965. Sediment after logging road construction in a small Oregon watershed. U.S. Dep. Agric. For. Serv., Misc. Publ. 970, Paper No 8.

Froehlich, H.A. 1973. The impact of even-age forest management on physical properties of soils. *In* Even-age Management Symposium. R. Herman and D. Lavender (editors). Ore. State Univ., Corvallis, Ore., pp. 199-219.

_____ . 1979. Soil compaction from logging equipment: effects on growth of young ponderosa pine. J. Soil Water Conserv. 1979 (6):276-278.

Froelich, H.A., J. Azevedo, D. Cafferata, and D. Lysne. 1980. Predicting soil compaction on forest land. U.S. Dep. Agric. For. Serv., Pac. NW For. Range Exp. Sta. and Missoula Eq. Div. Cent. Ore. St. Univ., Corvallis, Oregon. Final Report, Coop. Agreement 228.

Gent, J.A., R. Ballard, and A.E. Hassan. 1983. The impact of harvesting and site preparation on physical properties of Lower Coastal Plain soils. Soil Sci. Am. J. 47:595-598.

Greacan, E.L. and R. Sands. 1980. Compaction of forest soils: a review. Aust. J. Soil Res. 1980 (18):163-189.

Hager, H. and M. Sieghardt. 1984. [Damage to forest sites through soil compaction. I. Soil physical changes on soils of different textures.] Centralblatt fur das Gesamte Forstwesen. 101 (2):109-120. (From English summary in Forestry Abstracts.)

Haines, L.W., T.E. Maki, and S.G. Sanderford. 1975. The effects of mechanical site preparation treatments on soil, productivity, and tree growth. *In* Forest soils and forest land management. Univ. Laval Press, Montreal, Que. pp. 379-395.

Halverson, H.G. and R.P. Zisa. 1982. Measuring the response of conifer seedlings to soil compaction stress. U.S.Dept. Agric. NE For. Range Exp. Sta., University Park, Pa. Research Pap. NE-509.

Hatchell, G.E., C.W. Ralston, and R.R. Foil. 1970. Soil disturbance in logging. J. Forestry 68: 772-775.

Heilman, P. 1981. Root penetration of Douglas-fir seedlings into compacted soils. Forest Sci. 47:660-666.

Hildebrandt, E.E. 1983. [The influence of soil compaction on soil functions on forest sites.] Fortwissen schaftichis Centralblatt 102 (2): 111-125. From English summary.

Israelsen, C.E., C.G. Clyde, J.E. Fletcher, E.K. Israelsen, F.W. Haws, P.E. Packer, and E.E. Farmer. 1980. Erosion control during highway construction. Manual on principles and practices. Transportation Res. Board, Nat. Res. Council, Washington, D.C. Nat. Coop. Highway Res. Prog. Rep. 221.

Jakobsen, B.F. 1983. Persistence of compaction effects in a Forest Kraznozem. Aust. For. Res. 13:305-308.

Jakobsen, B.F. and G.A. Moore. 1981. Effects of two types of skidders and of a slash cover on soil compaction by logging of mountain ash. Aust. J. For. Res. 11(3/4):247-255.

Lewis, T. and Timber Harvesting Subcommittee. 1991. Developing timber harvesting prescriptions to minimize site degradation. B.C. Min. For., Victoria, B.C. Land Manag. Rep. 62.

Lewis, T., W.W. Carr, and Timber Harvesting Subcommittee. 1989. Developing timber harvesting prescriptions to minimize site degradation - Interior sites. B.C. Min. For., Victoria, B.C. Fieldguide insert.

Mace, A.C., Jr., T. Williams, and J.C. Tappeiner II. 1971. Effect of winter harvesting methods on soil bulk density and infiltration rates. Minn. For. Res. Note 228.

McNutt, J.A. and D. McGeer. 1985. Pitfalls in the strict reliance on expert opinion in assessing stability hazard. *In* Proc. Workshop on Slope Stability. U.S.Dept. Agric., Pac. NW For. Range Exp. Sta., Portland, Ore. Gen. Tech. Rep. PNW-180:36-42.

Minko, G. 1975. Effects of soil physical properties, irrigation, and fertilizer on *Pinus radiata* seedling development in the Benalla Nursery. For. Tech. Paper, For. Commission, Victoria (Australia) 22:19-24.

Mitchell, W.R. 1984. Interpretations for timber and silvicultural management in the Kamloops Forest Region. *In* Proc. Soil Management Implications in the Kamloops Forest Region. Dec. 13-14, 1984, Kamloops, B.C.

Mitchell, W.R. and R. Eremko. 1987. Ecosystem mapping of the Truax Creek Basin in the Kamloops Forest Region. B.C. Min. For. Lands, Victoria, B.C.. Res. Rep. RR87007-KL. 125 p.

Mitchell, M.L., A.E. Hassan, C.B. Davey, and J.D. Gregory. 1982. Loblolly pine growth in compacted greenhouse soils. Trans. ASAE (1982):304-307 and 312.

Moehring, D.M. and I.W. Rawls. 1970. Detrimental effects of wet weather logging. J. For. 68: 166-167.

Musgrave, G.W. 1947. The quantitative evaluation of factors in water erosion-a first approximation. J. Soil and Water Conserv., Vol. 2, pp. 133-138.

Perry, T.O. 1964. Soil compaction and loblolly pine growth. Tree Planter's Note No. 67.

Rice, R.M. and P.A. Datzman. 1981. Erosion associated with cable and tractor logging in northwestern California. *In* Erosion and sediment transport in Pacific rim steeplands. IAHS Pub. No. 132:362-374.

Rosewell, C.J. 1986. Soil erosion prediction in the United States. J. Soil Conserv. (Aust.) 42(2):133-134.

Ruarck, G.A., D.L. Maden, and T.A. Tattar. 1982. The influence of soil compaction and aeration on the root growth and vigour of trees - a literature review - Part I. Arborcultural J. 6:251-265.

Schwab, J.W. and W.J. Watt. 1981. Logging and soil disturbance on steep slopes in the Quesnel Highlands, Caribou Forest Region. B.C. Min. For., Victoria, B.C. Research Note No. 88.

Skinner, M.F. and G.D. Bowen. 1974. The penetration of soil by mycelial strands of ectomycorrhizal fungi. Soil Bio. Biochem. 6:57-61.

Smith, D.D. 1941. Interpretation of soil conservation data for field use. Agric. Engin. 22:173-175.

Smith, D.D., and D.M. Whitt. 1947. Estimating soil losses from field areas of claypan soils. *In* Proc. Soil Sci. Soc. Am., Vol. 12, 485-490.

Smith, R.B. and E.F. Wass. 1979. Tree growth on and adjacent to contour skidroads in the subalpine zone, southeastern British Columbia. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Rep. BC-R2.

_____. 1985. Some chemical and physical characteristics of skidroads and adjacent undisturbed soils. Can. For. Serv., Pac. For. Res. Cent., Victoria, B.C. Inf. Rep. BC-X-261.

Sowers, G.B. and G.F. Sowers. 1970. Introductory soil mechanics and foundations. The MacMillan Co., New York, NY.

Steinbrenner, E.C. and S.P. Gessel. 1955a. Effect of tractor logging on soils and regeneration in the Douglas-fir Region of southwestern Washington. *In* 1955 Proc. Soc. Am. For. pp. 77-80.

_____. 1955b. The effect of tractor logging on physical properties of some forest soils in southwestern Washington. Soil Sci. Soc. Proc. 19:372-376.

Swanston, D.N. 1974. Guidelines for characterizing naturally unstable or potentially unstable slopes on western national forests. *In* Proc. Symp. on New Requirements for Forest Road Construction, Dec. 9-11, 1974, Univ. B.C. Continuing Education, Vancouver, B.C , pp. 122-136.

Tackle, D. 1962. Infiltration in a western larch-Douglas-fir stand following cutting and slash treatment. U.S.Dept. Agric. Intermount. For. Range Exp. Sta., Ogden, Utah. Res. Note 89.

Thorud, D.B. and S.S. Frissell, Jr. 1976. Time changes in soil density following compaction under an oak forest. Minn. For. Res. Note 257.

van der Puy, M.E. 1987. Rating erosion susceptibility. *In* Proc. Conf. XVIII International Erosion Control Assoc., Feb. 26-27, 1987, Reno, Nevada.

van der Weert, R. 1974. Influence of mechanical forest clearing on soil conditions and the resulting effects on root growth. Trop. Agric. 51 (2):325-331.

Wert, S. and B.R. Thomas. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Sci. Soc. Am. J. 45:629-632.

Wischmeier, W.H. 1959. A rainfall erosion index for a universal soil-loss equation. *In* Proc. Soil Sci. Soc. Am., Vol. 23, pp. 246-249.

Wischmeier, W.H., C. B. Johnson, and B.V. Gross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil Water Conserv., Vol. 26, No. 5.

Wischmeier, W.H. and D.D. Smith. 1958. Rainfall energy and its relation to soil loss. Transactions, AGU, Vol. 39, No. 2, pp. 285-291.

_____ . 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. U.S. Dept. Agric., Agric. Hand. No. 282.

_____ . 1978. Predicting rainfall erosion losses: a guide to conservation planning. U.S. Dept. Agric., Agric. Hand. No. 537.